COMMON-MODE NOISE REDUCTION TECHNIQUES FOR SWITCHED-MODE POWER CONVERTERS

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Abstract: In various kinds of switched-mode power converters, conducted noise due to switching operation frequently causes interference with other electronic equipment. This paper focuses on the common-mode conducted noise generated in switched-mode power converters and presents three examples of noise reduction techniques. First, the common-mode conducted noise is reduced in a common-source type active-clamped DC-DC converter for IT equipment by canceling the switching noise current. Secondly, the common-mode current is controlled and reduced by damping impedance in motor drive systems. Thirdly, development of a DC-DC converter for scientific spacecraft use is presented, where very small common-mode noise current is required.

Key words: Common-mode conducted noise, Common-source type active clamped converter, Motor drive system, Scientific spacecraft

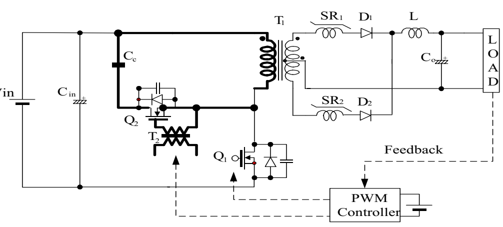
1. Introduction

Recently switched-mode power converters are widely used in many electronic equipments and power systems because of their advantages of high efficiency, small size, light weight and high controllability. However, in various kinds of switched-mode power converters, conducted noise due to switching operation frequently causes interference with other electronic equipment. The conducted noise is classified into two components, namely, the common-mode and the differential-mode. In many cases, the common-mode conducted noise is generated by parasitic capacitances between the voltage changing components in a power converter and the frame ground or metal case, so it is very difficult to suppress its noise level. Moreover, the common-mode conducted noise may cause more influence than the differential-mode conducted noise does because the loop area of the common-mode conducted noise usually becomes very large. So, it is necessary to reduce the common-mode conducted noise to a sufficiently low level.

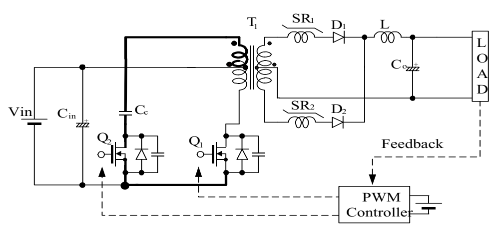
This paper focuses on the common-mode conducted noise generated in switched-mode power converters and presents three examples of noise reduction techniques. First, the common-mode conducted noise is reduced in a common-source type active-clamped DC-DC converter for IT (Information Technology) equipment by canceling the switching noise current. Secondly, the common-mode current is controlled and reduced by damping impedance in motor drive systems. Thirdly, development of a DC-DC converter for scientific spacecraft use is presented, where very small common-mode noise current is required.

2. Noise Reduction by Common-Source Type Active-Clamp Technique [1]

Active-clamp techniques with two active switches are used in DC-DC converters to reduce switching noise and switching loss by means of the soft switching. Figure 1 shows two kinds of DC-DC converter circuits with active-clamp techniques. The circuit shown in (a) is a conventional type and (b) is a common-source type. Two active switches Q_1 and Q_2 form the active-clamp circuit, and they are driven alternately with a small dead time to suppress the voltage surge and to realize the soft switching (ZVS). In the conventional type (a), the high-side switch Q_2 is driven by a pulse transformer T_2, and a parasitic capacitance between the drain of Q_1 and the frame ground through a heat sink may cause the common-mode conducted noise. On the other hand, in the common-source type (b), the source of Q_2 is directly connected to the source of Q_1, which makes the drive circuit very simple, so the isolation transformer is not needed anymore. Because the primary winding turns ratio of T_1 is 1:1, the drain voltages of Q_1 and Q_2 change by the same amount but in an opposite



(a) Conventional type



(b) Common-source type

Fig. 1. Active-clamp DC-DC converters.

polarity in their switching time. As a result the common-mode conducted noise is suppressed even when the parasitic capacitances exist for both of Q_1 and Q_2 between each drain and the frame ground.

In order to examine noise characteristics of these converters, a noise measurement system is set up as shown in Fig. 2. Figure 3 shows experimental results obtained by the conducted noise measurement, where (a) is for the conventional type and (b) is for the common-source type. Comparing these figures, it is found that the conducted noise is much reduced in the common-source type active-clamped converter.

Figure 4 shows the noise current path during turn off of Q_1 in the common-source type active-clamped converter. Because the drain voltages of Q_1 and Q_2 change by the same amount ΔV but in an opposite polarity, the current through C_{P1} is canceled by the current through C_{P2} provided $C_{P1}=C_{P2}$, and so the common-mode noise are well suppressed.

Figure 5 shows spectrum of the near-field magnetic radiated noise for the frequency range of 500kHz to 30MHz. In the conventional type (a), it is noticed that two large noise peaks are observed at the frequencies of 7.3MHz and 14.5MHz. On the other hand, in the common-source type (b), a large noise peak is observed at the frequency of 2.91MHz and 6.69MHz. In order to investigate the noise source, we performed the spatial scan on the converter board at

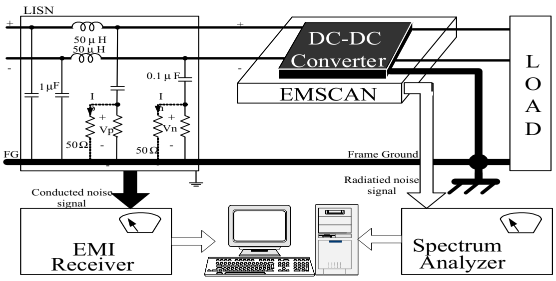
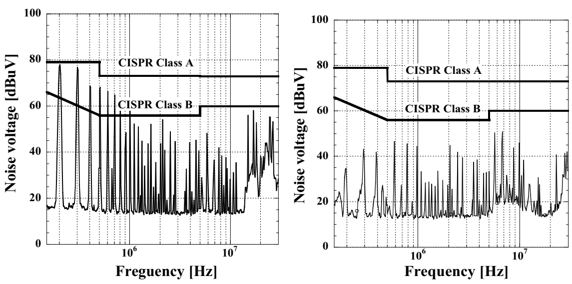


Fig. 2. Noise measurement system.



(a) Conventional type (b) Common-source type
Fig. 3. Experimental results of conducted noise.

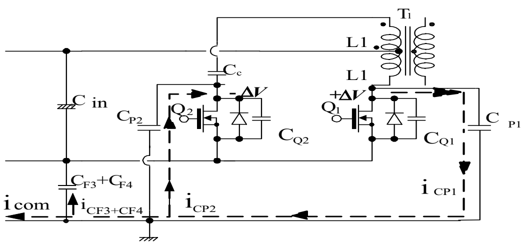
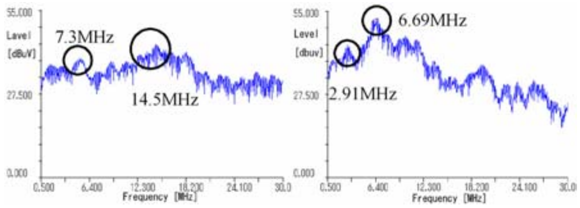


Fig. 4. Noise current path during turn off of Q_1.

these frequencies in problem. Figure 6 shows experimental results of the spatial scan, where (a) is for the conventional type and (b) is for the common-source type. In the conventional type (a), a high current path is observed in a large area of the converter board, especially in the neighborhood of the primary switches, main transformer T_1 and the pulse transformer T_2 at the high frequencies of 14.5MHz. It is estimated that the high frequency switching noise including the ringing noise is conducted and spread out over the large area. In the common-source type (b), whereas the high frequency noise is much reduced, low frequency noise of 2.91MHz and 6.69MHz is noticeable around the primary switches and the parasitic capacitances. It is considered that this noise is due to the high current flow through the parasitic capacitances C_{P1} and C_{P2} as shown in Fig. 4. So, it is very important to shrink the area of the current loop as much as possible to reduce the radiated noise.



(a) Conventional type (b) Common-source type
Fig. 5. Spectrum of the near-field magnetic radiated noise.

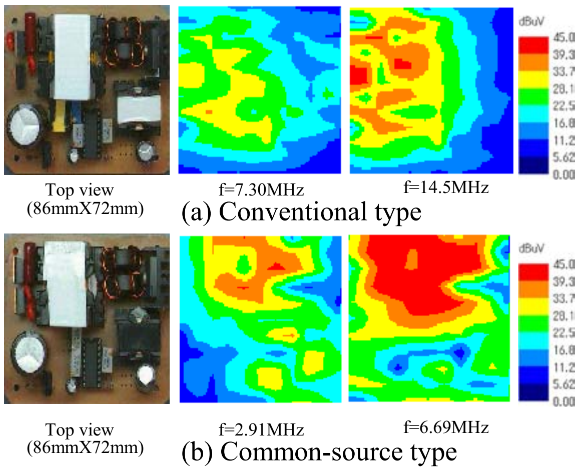


Fig. 6. Mapping of radiated noise by EMSCAN.

3. Common-Mode Current Control in Motor Drive Systems

Figure 7 shows assumed EMI noises transmission paths appearing in motor drive systems. There are two kinds of noise currents produced in the motor drive system, i.e. differential mode currents and common-mode currents (I_{C1}, I_{C2}, I_{C3}), which are transmitted into the ground via the ac reactor frame, the cooling fin, and the motor frame. Figure 8(a) shows measured common-mode currents flowing into the ground from the motor frame, and FFT analyzed results of their waveforms. It is confirmed from Fig. 8(b) that the series resonance phenomena occur at frequencies of 1.8MHz, 3.5MHz and 17MHz. It has also verified by [2] that common-mode currents flow due to series resonance phenomena which are generated due to voltage fluctuations produced by switching operations of the power converters and surge voltages appearing at terminals of the ac reactor and motor. As shown in Fig. 9, it was clarified by the experiments that common-mode currents flow on current paths while being excited by voltage sources with frequencies of 1.8MHz, 3.5MHz, 14.5MHz and 17MHz which are produced on the converter and inverter sides.

A method to control common-mode currents flowing these common-mode current paths is proposed that prevents series resonance phenomena by adding a damping impedance between the machine frame and the ground. In order to determine damping impedances suitable for suppressing series resonance phenomena, circuit parameters (*R, L, C*) for common-mode current paths must be researched. First, the series resonance frequency components are derived from common-mode currents using the FFT band-pass filter technique, and then, circuit

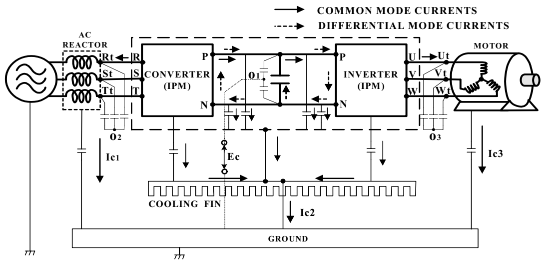
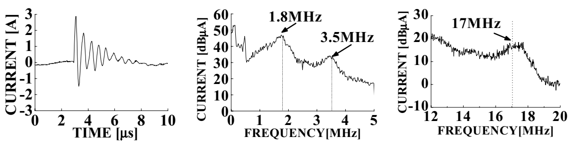


Fig. 7. EMI noise transmission paths appearing in motor drive systems.



(a) Current waveform. (b) FFT analyses of Fig. (a).

Fig. 8. Common-mode current flowing into the ground from the motor frame and its FFT analyses.

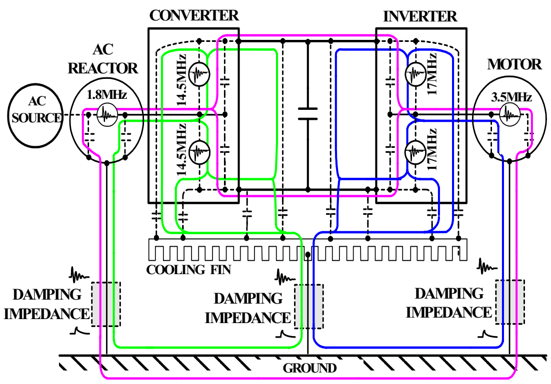
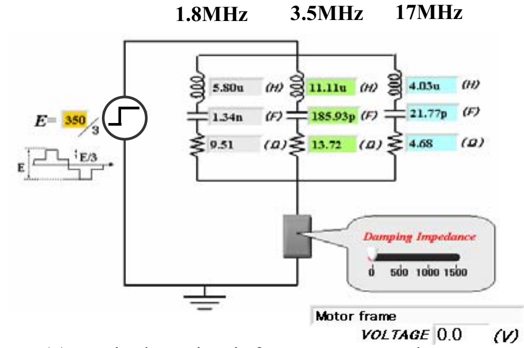
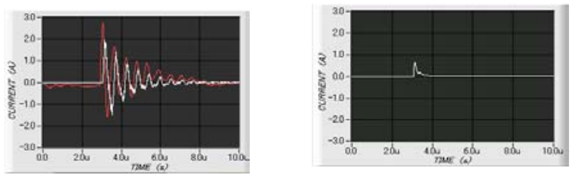


Fig. 9. Common-mode current paths producing in motor drive systems.

parameters for each resonance frequency, for instance, as shown by Fig. 10, are obtained through the transient waveform analysis. Next, the damping impedances suitable for suppressing the common-mode currents are estimated using the equivalent circuits which are formed based on the obtained parameters. Finally, safety being also considered, the damping impedances are determined so as to suppress the increase in the voltage of the machine frame. As seen from Fig. 11 indicating the suppression effects of the common-mode currents appearing on the motor side, effectiveness of the proposed method was verified through experiments over the whole motor drive system.



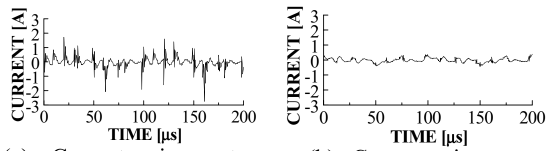
(a) Equivalent circuit for common-mode currents.



(b) Common-mode currents without suppressing any damping impedance.

(c) Simulation result when using the suitable damping impedance.

Fig. 10. Equivalent circuit for common-mode currents on motor side.



(a) Current via motor frame without control.

(b) Current via motor frame with control.

Fig. 11. Effects of the proposed common-mode current suppression method (applied damping impedance: 150Ω).

4. Development of DC-DC Converter for Scientific Spacecraft Use

In a scientific spacecraft, all the resources such as weight, size, and power are strictly limited. In addition, severe EMC specifications are often required especially when wave instruments are onboard. Sensitivity of the wave sensors is of the order of 10^{-7} V/m/Hz$^{1/2}$ for electric component and 0.1 pT/Hz$^{1/2}$ for magnetic component. EMC specifications are often set not to exceed sensor noise level at antenna position. Therefore CE-01, 03 and RE-02, 04 specifications are set at extremely lower value. Figures 12-14 show CE-01 and 03, RE-02, and RE-04 specifications (GEOTAIL PRELAUNCH REPORT, 1992) for GEOTAIL spacecraft, which was launched on 1992 to investigate Earth's magnetosphere, as an example, respectively.

As seen from Figs. 12-14, EMI clean DC-DC converters are essentially required for the scientific spacecraft. However, currently available commercial DC-DC converters for space use are concentrated to the size and weight, and EMC is considered poorly. As an EMC specification, only normal mode is considered, but common-mode, which is essential to achieve low EMI, is not considered. Common-mode

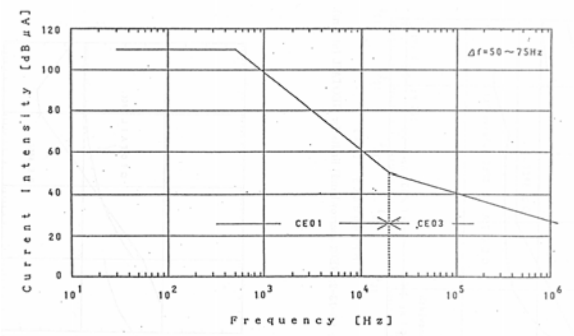


Fig. 12. CE01 and CE03 specifications.
(Fig. 1.5-13-1, GEOTAIL PRELAUNCH REPORT, 1992)

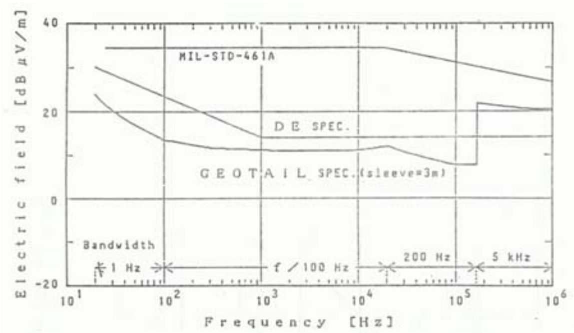


Fig. 13. RE02 specification.
(Fig. 1.5-13-2, GEOTAIL PRELAUNCH REPORT, 1992)

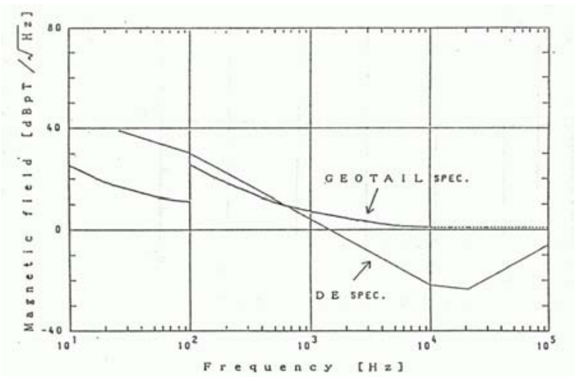


Fig. 14. RE04 specification at 60cm from each instrument.
(Fig. 1.5-13-3, GEOTAIL PRELAUNCH REPORT, 1992)

noise current for commercial DC-DC converters is usually of the order of several 10mA, and is too high to satisfy EMC requirement for scientific spacecrafts. Furthermore, DC-DC converters with 3.3V output voltage, which are used for recently developed ICs, have conversion efficiency of less than 70%. If the noise filter is attached to reduce common-mode noise current, the efficiency is estimated to decrease to lower than 60% and the weight increases up to several 100gr. Hence we have developed the EMI clean DC-DC converter with the specifications below by using the active-clamp technique:

Input voltage: 28V,
Outputvoltage: 3.3V (10W maximum)
Output voltage ripple <1mVp-p
Efficiency >80% (at Maximum load)
Weight <110gr (with case)
Common-mode current (DC-40MHz, RBW 3kHz)
Ave. <5μA, Peak <30μA

Common-mode noise current of the developed DC-DC converter is shown in Fig. 15, where peak and average currents are less than 20μA and 2μA, respectively.

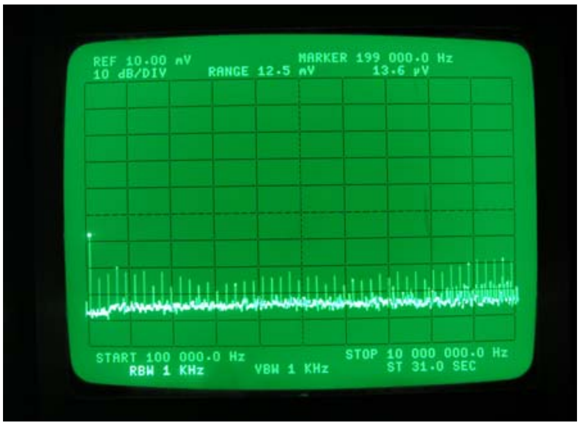


Fig. 15. Common-mode noise current of the developed DC-DC converter.
(Reference: 10mA, DC-10MHz.)

5. Conclusion

The common-mode conducted noise generated in switched-mode power converters is focused and three examples of noise reduction techniques are presented.

The authors would like to express their gratitude for the financial supports of a program entitled "Research for the Future" of Japan Society of the Promotion of Science.

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